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Simulation Modeling of Mobile Detection Systems

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Summary

Vehicles or small boats transporting radioactive materials could be detected by mounting radiation detectors on patrolling vehicles or vessels. In this report, we describe a simulation model developed to evaluate the efficacy of a given configuration of detectors and general concept of operations (CONOPS) attempting to detect a radioactive source. We characterize performance in terms of the probability that a detector system will encounter a source and the probability that the source will be detected given the encounter.

The simulation model includes parameters such as the bay length-to-width ratio (a rectangular bay is assumed), maritime traffic volume, radiation detection hardware, alarming algorithm, and patrol vessel CONOPS. In the model, the source-bearing vessel enters one end of the bay and attempts to reach the opposite side of the bay. Patrol vessels deployed in the bay attempt to screen all incoming vessels in accordance with the specified CONOPS. For each setting of input parameters, thousands of simulation runs are made to estimate the average performance of the system.

Introduction

In this paper, we focus on maritime detection assets that are deployed in rivers or bays. To evaluate the efficacy of a given fleet configuration and CONOPS, we utilize a continuous-time simulation model to estimate three key performance parameters: probability that a detector-equipped boat or helicopter will encounter a source, probability that the source will be detected given the encounter and the range from target at which the source is detected. The model was initially developed to support planning efforts at the Department of Homeland Security [Edmunds 2009].

The model is intended to analyze a postulated source in a small boat entering a bay or moving up a river next to a major city. The source-bearing vessel is assumed to enter one end of the bay (likely from international waters) or river, and attempts to reach the opposite side of the bay or further up the river. The simulation takes place on a rectangle, which can be sized to match the area of interest. For example, the simulation analysis described in this report is conducted for a 10 km by 5 km rectangle. This is roughly equivalent to the dimensions of New York Bay, so overall results of the analysis may be relevant for New York. Similarly, the 10 km length of the Potomac River south of Washington could be represented by a 10 km x 1 km rectangle. The San Diego Bay from Point Loma to the City of San Diego could also be represented by a 10 km x 1 km rectangle. Its curvature is not significant for the maritime surveillance activities modeled here.

A small vessel carrying a source is assumed to enter the bay at a random time and location at the mouth of the bay or from up river (one edge of the rectangle). The vessel proceeds directly to the target city at the opposite end of the bay unless it is detected and interdicted by patrol vessels.

Traffic patterns for small commercial vessels and pleasure craft can be variable over space and time. We attempt to capture some of the spatial patterns in the simulation by including several marinas from which small commercial and pleasure craft depart and either execute random trajectories within the bay or exit via the mouth of the bay. Additional vessels enter at the mouth of the bay and follow randomized trajectories to various points in the bay.

Radiation Transport

Both detection and nuclide identification of radiation sources are adversely affected by intervening material between the source and detector. For a source located below deck but above the waterline, the hull material or the ship's deck provides some amount of radiation shielding. Typical hull materials and their thicknesses for vessels weighing less than 300 tons were used. In general, metal boats in this size range are plated with 3/16" to 1/4" (0.48-0.64 cm) steel or 3/8" (0.95 cm) aluminum. Wood hulls are generally on the order of 1" to 2" (2.54 – 5.08 cm) thick and fiberglass hulls are ½" to 1" (1.27-2.54 cm). We evaluated the effect of various hull types on the radiation signatures of a number of radiation detection benchmark sources. The hull types and thicknesses we considered are:

- Steel – 0.5 cm
- Aluminum – 1.0 cm
- Wood – 5.0 cm
- Fiberglass/epoxy – 2.0 cm

The gamma attenuation is energy dependent, but for a specific energy is given in **Equation 1**:

$$S(t) = \frac{M}{r(t)^2}\cos(\theta)e^{-\mu\rho x} \quad \textbf{[1]}$$

where M = counts/sec in 2"x4"x16" NaI detector at a range of 1 meter
r = range from source to detector (meters)
θ = angle between source-detector vector and vector normal to the plane of detector surface
μ = mass attenuation coefficient for the specified energy (cm^2/g)
ρ = material density (g/cm^3)
x = shield thickness (cm)

Typical material properties and attenuation factors for these hull types and a 662 keV gamma from ^{137}Cs are shown in the first four lines of data in **Table 1** [Lamarsh 1975]. As indicated by the data in the table, 70-80% of the gammas will pass through the hull material without interaction. Attenuation due to water is also shown in the table. Note that 1 meter of water will interact with 99.99% of the gammas. Hence, if a source is located below the waterline and the detector is low so that a line of sight to the detector must pass through a meter of water, the source will likely be undetectable. This illustrates the advantage of mounting a detector on the mast of a patrol craft or on a helicopter. Finally, the data in the table indicate that 100 meters of air will scatter 65% of the gammas. Some fraction of the scattered gammas can reach the detector. These scattered gammas can contribute to the signature for detection, but can complicate the nuclide identification function.

Table 1 Attenuation of 662 keV gammas from ^{137}Cs

Material	Thickness (cm)	Mass attenuation coefficient (cm^2/g)	Density (g/cc)	Transmission factor
Fe	0.5	0.076	7.9	0.74
Al	1.0	0.078	2.7	0.81
Wood*	5.0	0.080	0.9	0.70
Fiberglass*	2.0	0.080	1.6	0.77
Water	100	0.090	1.0	0.00012
Air	10,000	0.080	0.0013	0.35

* Assumed same as carbon

Detection Algorithms

We consider detection algorithms based only upon the gross counts in the detector. For our initial analyses, we assume an unobstructed line of sight between the source and the detector. That is, we assume that the source is located above the waterline and air attenuation is negligible for the distances we are considering. We also ignore the 20-30% attenuation of the signal that would occur in the hull. Finally, secondary photons from Compton scattering off of the water would also contribute to the flux, but are not included in the current analysis.

k*sigma Detection Algorithm

The simulation model includes a simple "*k*sigma*" threshold algorithm[1] for radiation detection with *k* set at 5 and a default 6 second signal integration time. Alternative integration times can be selected by the user in one second increments. An alarm occurs when the number of counts observed in the detector during a 6 second time interval exceeds the mean background rate plus five times the background standard deviation ($B + 5\sqrt{B}$ where B is the average background rate). As stated in Section 2.0, a typical ambient background rate for a 2"x4"x16" NaI detector over 50 meters from shore is 40 cps. The probability of observing a background signal that exceeds five sigma in any one second interval is 3.4 x 10^{-6}. Thus, we can expect to observe one false alarm every three days per patrol vessel due to background fluctuations alone. Note that if patrol vessel operators were willing to tolerate one false alarm every few hours, the detection threshold could be lowered to the four sigma level.

The k*sigma detection algorithm aggregates detector signals within a finite time window to detect radiation levels that are above estimated background levels. Detector signals will only be elevated during the time the source comes closest to the detector. If the time window for analysis is too short, the algorithm will fail to exploit the entire signal that the source generates. If the time window is too long, the signal will be contaminated with background measurements when the source is no longer close to the detector. In the simulation code, the user can select a time window to use for the k*sigma algorithm that takes into account these considerations. We have also implemented a dynamic time window that takes into account the range and relative speed of the source and detector. This dynamic time window approximates an optimal time window when background is well known, and is frequently used to compare alternative detection hardware and algorithms.

Minimum Detectable Source Intensity

Physical variables such as background radiation, detector volume, range, and count time influence the ability to detect sources. Two key policy variables are the allowable false alarm rate due to background and the desired probability of detecting a source. When these physical variables describing the encounter and policy variables are set, the minimum detectable source intensity can be calculated.

First, variables that describe the encounter are established. For the base case analysis in this study, background radiation is 40 cps in a 2"x4"x16" NaI detector, and the source-detector range is maintained at 15 meters during the inspection. The count time for this example is 6 seconds, which corresponds to one time step in the simulation analyses described later in the report. Given this background count rate and time window, the Poisson probability distribution of observed background counts is shown as the blue curve in **Figure 1.** As indicated by the data in the figure, the mean background count for this 6 second window is 240.

[1] The threshold is defined as: $B + k*sigma$, B = average background and $sigma = \sqrt{B}$ for Poisson background.

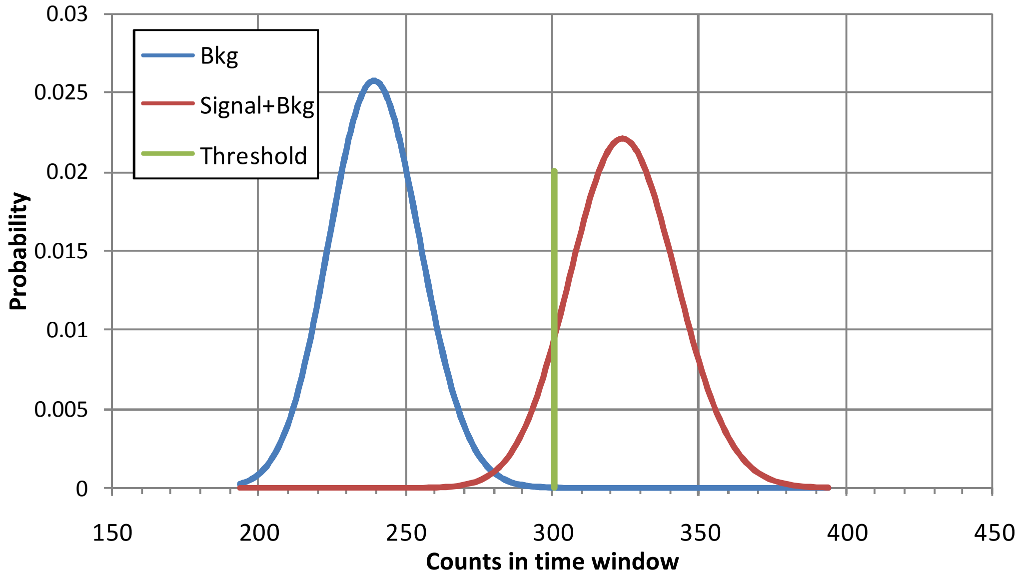

Figure 1 Detection threshold and minimum detectable source intensity

If the desired false alarm rate is one per day, the probability of an alarm from background in each 6-second interval must be $6.94x10^{-5}$ (= 6/(24*3,600)). For a Poisson probability distribution[2] with a mean of 240 counts, the probability that an observation will exceed 301 counts is $6.5x10^{-5}$. Hence, setting a threshold of 301 counts in a 6 second window will result in an average of approximately one false alarm per day. This threshold is depicted as the vertical green line in the figure.

The addition of a source (signal) would generate counts with the probability distribution shown as the red curve on the right side of Figure 3-12. Stronger sources will shift the curve to the right. The probability of detection of a given source corresponds to the integral of the distribution to the right of the threshold. If the desired probability of detection is fixed, the source strength with this integral can be computed. In the example in the figure, the probability of detection was fixed at 0.9, and the corresponding mean signal strength is 84 counts in a 6 second window at a range of 15 meters (or 3,150 cps at 1 meter).

Detection performance can be improved by increasing the time window for counting. As indicated by the blue curve in **Figure 2,** the minimum detectable source strength can be reduced to 1,250 cps by increasing the time window from 6 to 30 seconds. Performance improvement is less dramatic for further increases in the time window; doubling the time window to 60 seconds only reduces the minimum detectable source intensity by about one third to 800 cps.

[2] Although radiation measurement statistics follow a Poisson distribution, a Normal approximation is often used for analysis. In this example, a Normal distribution approximation yields a threshold of 299 rather than the true value of 301 counts. Use of this lower threshold would result in a false alarm probability of $1.05x10^{-4}$, or 51% higher than the required 1 false alarm per day.

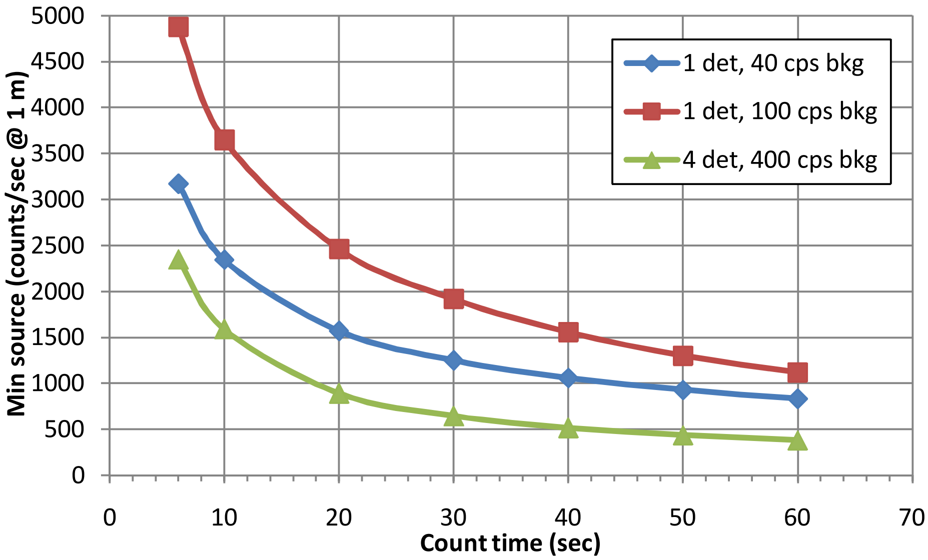

Figure 2. Minimum detectable source as a function of background, count time and detector volume

While our base case analysis uses a background of 40 cps, other researchers have measured higher backgrounds at other deployments. If background increases to 100 cps, the minimum detectable intensity will increase to almost 5,000 cps for a 6 second count window, as shown in the figure (red curve). Longer count windows would be needed to improve sensitivity. Alternatively, more detector volume could be deployed. Using four 2"x4"x16" NaI detectors would increase background to 400 cps, but would decrease the minimum detectable source intensity as shown by the green curve in the figure. In this instance a key design tradeoff is: increase count time from 6 to 20 seconds or increase detector volume to 4 detectors and maintain the 6 sec count time. Costs and other considerations would be needed to compare these two design options at a given venue.

Sequential probability ratio test with early termination

The simulation described in the next section also implements a modified version of Wald's sequential probability ratio test (SPRT) with early termination as the default detection algorithm [Lindgren 1976]. Wald's SPRT is a sequential hypothesis test that is useful when observing a random process over time. We define the following variables.

f_1 = the probability density function of the background radiation
f_2 = the probability density function of the source + background radiation
P_{fp} = target false positive probability
P_{fn} = target false negative probability
a = positive threshold = $\log \dfrac{1-P_{fn}}{P_{fp}}$

b = negative threshold = $\log \dfrac{P_{fn}}{1-P_{fp}}$

After each counting period i, the observation during that period, $totalCounts_i$, is used to compute the log likelihood ratio

$$\gamma_i = log\frac{f_2(totalCounts_i)}{f_1\,(totalCounts_i)} \qquad \textbf{[2]}$$

which is then cumulatively summed as

$$Z_i = \sum_{i=1}^{n} \gamma_i. \qquad \textbf{[3]}$$

Since the background and source radiation are modeled as Poisson processes, and the sum of two independent Poisson random variables is a Poisson random variable, Equation 3-1 can be evaluated as

$$\gamma_i = \log\frac{f_2(\mathrm{totalCounts_i})}{f_1\,(\mathrm{totalCounts_i})} = \log\frac{\lambda_2}{\lambda_1} total\mathrm{Counts_i} - \left(\lambda_2 - \lambda_1\right)\Delta\mathrm{T} \qquad \textbf{[4]}$$

where λ_i is the rate parameter for the Poisson random variable corresponding to f_i and ΔT is the time interval during period i. If, and when, Z_i reaches or crosses one of the thresholds, a or b, the algorithm ends. That is,

$$if\ Z_i \begin{cases} \geq a & source\ present \\ \leq b & no\ source\ present \\ otherwise & continue\ observing \end{cases}$$

If neither threshold a or b is reached by a predetermined maximum run time (i.e. $b < Z_i < a$ *and* $i \geq$ *max run time)*, then a benign ship is decided. By deciding a benign ship when the maximum run time is reached, the resulting false negative rate may be higher than the resulting false positive rate, but the resulting false positive rate will have the desired property of being very close to the target false positive rate P_{fp}.

Unlike the k*sigma algorithm, SPRT has the benefit that it provides an “all-clear” indication, in addition to raising an alarm for potential source signal. SPRT is known to have very small average sample size (count duration), and provides a convenient way to set false positive and false negative probabilities.

Both the k*sigma and SPRT algorithms are implemented at inspection, that is, when the patrol ship gets within a specified distance (denoted as detection range) from the suspect ship. Either algorithm can also be implemented in a continuous mode while the patrol is not actively inspecting any ship. In this case, when an alarm is raised, the patrol ship will pursue the nearest ship in order to obtain a better reading and determine whether the ship contains a source. When the SPRT algorithm is continuously computing a ratio while the patrol ship is travelling the bay and not within the detection range of any other vessel, we set $b=0$ [Nelson 2007] so that the lack of counts in one area does not bias the results for the next area. That is, if Z_i has been tending towards an “all clear” and is close to the threshold value b while the patrol ship is travelling the bay and it eventually begins receiving counts from a source, Z_i would have to increase by nearly $|b| + a$ to reach the alarm threshold value of a. By setting $b= 0$ we essentially remove the ability to declare an "all clear" (or, equivalently, falsely declares "all clear" whenever Z_i is non-negative), but remove the bias in the alarm threshold described above.

The SPRT implemented during a pass-by encounter is a modified version of the SPRT described above. These vessels are at different distances with different headings. If and when the modified SPRT algorithm detects an alarm in such a situation, the patrol will immediately begin to pursue the nearest vessel to get within the detection range and implement the original SPRT algorithm in order to more accurately determine whether or not the vessel contains a source.

Analysis of Maritime Defense Architectures

In this section, we simulate an ensemble of radiation detectors deployed in the bay. In the simulation, a vessel carrying a one Ci ^{137}Cs source enters the mouth of the bay and attempts to reach the opposite end of the bay. A population of small commercial and pleasure craft routinely travel through the bay. The source-bearing vessel must be detected and identified within this population of benign vessels.

We assume NaI detectors are mounted on patrol craft in the bay. Detectors include one or more 2"x4"x16" NaI crystals, photomultiplier tubes, electronics and spectroscopic identification algorithms that run in an automated mode. The identification algorithms are assumed to be capable of discriminating between nuisance sources on boats and sources of interest.

Detectors are mounted on one side of the patrol boat pointing outward. Typical operations would occur in protected bays where we assume that seas are relatively calm and boat rocking would not significantly degrade performance. To support operation in heavier seas, detectors could be mounted on gimbals to maintain a favorable geometry between source and detector. The CONOPS for boat-mounted detectors is to select the nearest suspect vessel for inspection, maneuver to a parallel course at a desired range (the "detection range"), start the detection system and maintain course until the detection system signals an interdict or clear command. The mission is to inspect as many as possible inbound vessels on a routine basis.

Key base case parameters in this simulation model include:

- 30 vessels/hour in bound that must be screened
- 4 NaI detectors
- 2 patrol boats assigned to two zones in bay
- 15 meter range between inspected vessel and patrol boat during screening operations
- 5 sigma threshold set for k-sigma algorithm
- 0.001 SPRT target false positive rate and 0.01 SPRT target false negative rate
- 5 minute SPRT maximum run time
- 10km by 5km bay
- 1,000 simulation samples
- Max ship speed 9 knots (uniform between 4.5 and 9 knots)
- Patrol ship speed 10 knots

Results of the simulation are shown in **Figure 3**. The SPRT algorithm is used with the base case parameters as described above. As shown in the figure, two patrol boats are needed to ensure an 87% probability of detection when the arrival rate is 20 incoming ships per hour. Three patrol boats are necessary when the arrival rate is increased to 80 ships per hour. The SPRT detection probability is asymptotic at 0.9 because the false negative parameter for the algorithm is fixed at 0.1. This reduces the required scan time per boat and allows a single patrol vessel to inspect more inbound boats.

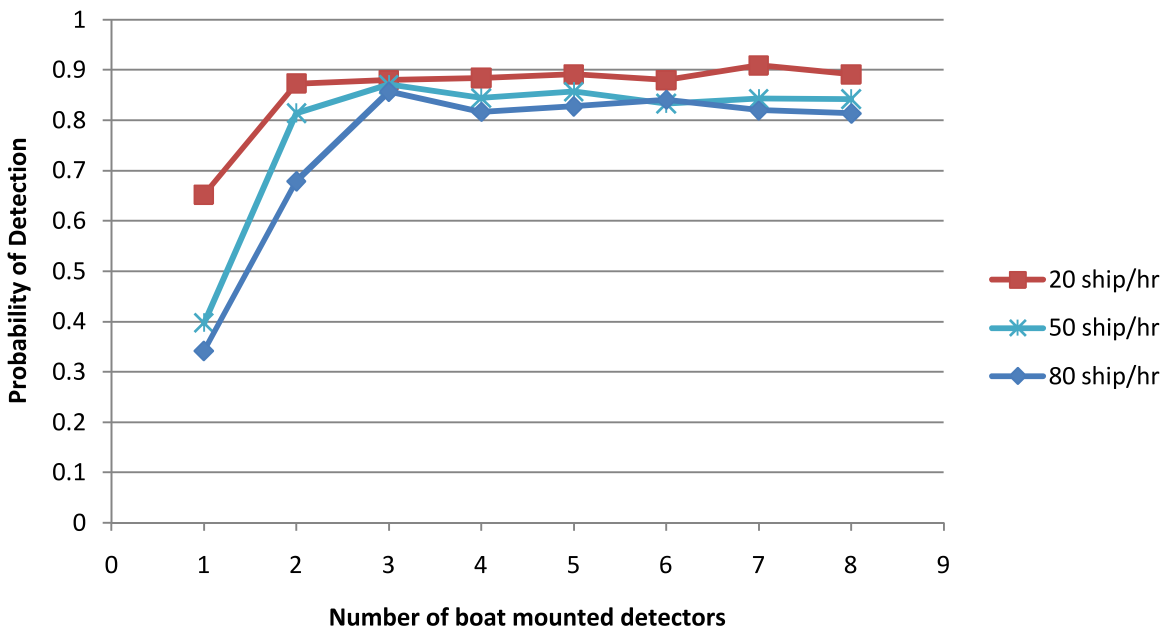

Figure 3. Probability of detection

Summary and Conclusions

Simple radiation transport models have been used to develop a simulation model for evaluating the effectiveness of a fleet of detector- equipped patrol boats attempting to interdict a source. The model accounts for shielding from the boat hull and includes two basic detection algorithms. User-specified parameters characterize the maritime environment in which the patrol boats and screened boats interact, the sources of interest, radiation detector characteristics and patrol fleet CONOPS. Results of simulation analyses can be used to determine the number of patrol boats and detector types needed to achieve a specified performance level in a given maritime environment.

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